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Detection of massive supernova neutrinos

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Abstract. Neutrinos and antineutrinos of all three flavours are emitted during the post bounce phase of a core collapse supernova with $\nu_\mu/\nu_\tau(\bar{\nu}_\mu/\bar{\nu}_\tau)$ having average energies more than that of $\nu_e(\bar{\nu}_e)$. They can be detected by the new earth bound detector like SNO and Super-Kamiokande. We present the effect of flavour oscillations on the neutrino flux and their expected number of events at the detector. We do a three-generation analysis and for the mass and mixing schemes we first consider the threefold maximal mixing model consistent with the solar and the atmospheric neutrino data and next a scenario with one $\Delta m^2 \sim 10^{-11}eV^2$ (solar range) and the other $\Delta m^2 \sim 10^{-18}eV^2$, for which the oscillation length is of the order of the supernova distance. In both these scenarios there are no matter effects in the resultant neutrino spectrum and one is concerned with vacuum oscillations. We find that though neutrino oscillations result in a depletion in the number of ν_e and $\bar{\nu}_e$ coming from the supernova, the actual signals at the detectors are appreciably enhanced.

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1. Introduction

The entire subject of supernova (SN) ν detection started in February 1987 when KII and IMB detected 11 and 8 ν events respectively, which were associated with the explosion of SN1987A. Supernova neutrino detection is important for two reasons; firstly by studying them we can learn about the SN explosion mechanism as only the neutrinos come out of the preSN core carrying with them all the information and secondly the SN neutrinos can give lots of information on neutrino mass and mixing. In a type II SN about 10^{53} ergs of energy is released of which only 1% goes into the explosion and all the rest is carried away by the neutrinos. The emitted neutrinos can be classified into two categories, the pre-trapping neutrinos and the postbounce neutrinos. The pre-trapping neutrinos are released as a result of electron captures and the effect of flavor mixing on them has been considered in [1]. We will concentrate on the postbounce neutrinos. The postbounce neutrinos and antineutrinos come in all the 3 flavors with $\nu_\mu/\nu_\tau(\bar{\nu}_\mu/\bar{\nu}_\tau)$ having average energies more than that of $\nu_e(\bar{\nu}_e)$. For massive neutrinos coming from a galactic SN, we can expect to see two effects on the neutrinos signal in the terrestrial water Cerenkov detectors. Firstly, massive neutrinos will move at a speed less than the speed of light and will be delayed in time and secondly if in addition to mass, neutrinos also have flavor mixing then the resultant neutrino spectra is modified. We find that though neutrino oscillations result in a depletion in the number of ν_e and $\bar{\nu}_e$ coming from the supernova, their actual signals at the detectors are appreciable enhanced.

2. Massive neutrinos and time delay

The current limits on neutrino masses from direct laboratory experiments are exceedingly unsatisfactory [2]. The time-of flight measurements of supernova neutrinos have been considered to be the most promising method to put limits on neutrino masses. A neutrino with mass m (in eV) and energy E (in MeV) in traveling a distance D (in 10 kpc) will be delayed (in s) relative to a massless neutrino by

$$\Delta t(E) = 0.515(\frac{m}{E})^2 D \tag{1}$$

The SNO and Super-Kamiokande (SK) can detect on average a delay of 0.1 s. Most of the time dependence of the signal comes from the time dependence of the neutrino luminosity. As a result of this time delay, the shape of the event rate as a function of time changes in comparison to the one for massless neutrinos, depending on the amount of delay and hence on the neutrino mass. This difference in shape can be studied by doing a χ^2 analysis and limits on neutrino mass can be put. Another way is to compare the average arrival time of the massive neutrinos with that for massless neutrinos and use the statistical power of the SK and SNO to put such limits [3]. There have been other suggestions before such as determining the neutrino mass limits from the neutral current to charged current ratio [4].

3. Neutrino signal with flavor oscillations

The differential number of neutrino events at the detector for a given reaction process is

$$\frac{d^2S_\nu}{dEdt} = \frac{n}{4\pi L^2} N_\nu(t)\sigma(E)f_\nu(E) \tag{2}$$

One uses for the number of neutrinos produced at the source $N_\nu(t) = L_\nu(t)/\langle E_\nu(t)\rangle$ where $L_\nu(t)$ is the neutrino luminosity and $\langle E_\nu(t)\rangle$ is the average energy. In (2) $\sigma(E)$ is the reaction cross-section for the neutrino with the target particle,

L is the distance of the neutrino source from the detector(10kpc), n is the number of detector particles for the reaction considered and $f_\nu(E)$ is the energy spectrum for the neutrino species involved. For the neutrino luminosity and average energy we use the values of Totani *et al.* [5] for a 20 $M_\odot$ type II supernova model based on the hydrodynamic code developed by Wilson and Mayle. Though in their paper Totani *et al.* observe that the neutrino spectrum is not a pure black body, but we as a first approximation use a Fermi-Dirac spectrum for the neutrinos, charaterised by the ν temperature alone for simplicity. We find the ν signal for the various detection processes as a function of energy by integrating out time from (2). By integrating (2) over energy as well we get the total number of events for the reaction concerned. These are the expected number of events.

In the presence of oscillations of massive neutrinos more energetic $\nu_\mu(\bar{\nu}_\mu)$ and $\nu_\tau(\bar{\nu}_\tau)$ get transformed into $\nu_e(\bar{\nu}_e)$ which modifies the numbers that we obtain using (2). The general expression for the probability that an initial ν_α gets converted to a ν_β after traveling a distance L in vacuum is

$$P_{\nu_\alpha\nu_\beta} = \delta_{\alpha\beta} - 4\sum_{j>i} U_{\alpha i}U_{\beta i}U_{\alpha j}U_{\beta j}sin^2\frac{\pi L}{\lambda_{ij}} \tag{3}$$

where $\alpha = e, \mu, \tau, ..$ and $i, j = 1, 2, 3$
$\lambda_{ij} = 2.5 \times 10^{-3} km \frac{E}{MeV}\frac{eV^2}{\Delta m^2_{ij}}$
$\Delta m^2_{ij} = m^2_j - m^2_i$
$U_{\alpha i}$ are the components of the mixing matrix. For the mass and mixing parameters we consider two scenarios.

Scenario 1: Here we consider threefold maximally mixed neutrinos with the mass spectrum $\Delta m^2_{13} \approx \Delta m^2_{23} \sim 10^{-3}eV^2$ corresponding to the atmospheric range while $\Delta m^2_{12} \sim 10^{-11}eV^2$ in accordance with the solar neutrino problem. The oscillations due to all the mass differences are averaged out to 1/2 as $\lambda << L$, and hence the expression for the various probabilities in this case relevant for us are [6, 7]

$$P_{\nu_e\nu_e} = \frac{1}{3} \tag{4}$$

$$P_{\nu_\mu\nu_e} + P_{\nu_\tau\nu_e} = 1 - P_{\nu_e\nu_e} \tag{5}$$

We call this Case 1.

Scenario 2: Here we set $\Delta m^2_{12} \sim 10^{-18}eV^2$ for which $\lambda \sim L$ and the oscillation effects are observable while $\Delta m^2_{13} \approx \Delta m^2_{23} \sim 10^{-11}eV^2$ (solar range). If we consider the Maiani parametrisation of the mixing matrix U then the expression for the probabilities are

$$P_{\nu_e\nu_e} = 1 - sin^2 2\theta_{12}cos^4\theta_{13}sin^2\frac{\pi L}{\lambda_{12}} - \frac{1}{2}sin^2 2\theta_{13} \tag{6}$$

$$P_{\nu_\mu\nu_e} + P_{\nu_\tau\nu_e} = 1 - P_{\nu_e\nu_e} \tag{7}$$

For this case the oscillations due to Δm_{13}^2 and Δm_{23}^2 are averaged out as the neutrinos travel to earth but those due to Δm_{12}^2 survive. For θ_{13} we consider two sets of values allowed by the solar ν data. Out calculation is for $\sin^2 2\theta_{13}$ = 1.0 (the maximum allowed value) and with $\sin^2 2\theta_{13} = 0.75$ (the best fit value) [8]. The first set is called Case 2a while the second is called Case 2b. Since nothing constrains Δm_{12}^2 in this scenario we can vary θ_{12} and study it's effect on the ν signal. We have tabulated our results for $\sin^2 2\theta_{12} = 1.0$ since it gives the maximum increase in the signal from the no oscillation value.

The corresponding expressions for the antineutrinos will be identical. We note that because the energy spectra of the ν_μ and ν_τ are identical, we do not need to distinguish them and keep the combination $P_{\nu_\mu\nu_e} + P_{\nu_\tau\nu_e}$. We have made here a three-generation analysis where all the three neutrino flavours are active. Hence if both the solar ν problem and the atmospheric ν anomaly require ν oscillation solutions, then in the **Scenario 2**, the atmospheric data has to be reproduced by $\nu_\mu - \nu_s$ oscillations. We are interested in this scenario as only with neutrinos from a supernova can one probe very small mass square differences $\sim 10^{-18} eV^2$. To find the number of events with oscillations we will have to fold the expression (2) with the expressions for survival and transition probabilities for the neutrinos for all the cases considered.

In principle one should take into account the effect of the dense SN matter on the flavor mixing. But for the case of maximal mixing model (**Scenario 1**), it has been shown both numerically [9] and analytically [10] that there are no matter effects. Also for the **Scenario 2** the adiabaticity condition is strongly broken for both the Δm^2 's and hence matter effects are negligible [11].

reaction	signal without oscillation	signal with oscillation		
		Scenario 1	**Scenario 2**	
		Case 1	Case2a	Case2b
$\nu_e + d \to p + p + e^-$	78	155	150	153
$\bar{\nu}_e + d \to n + n + e^+$	93	136	133	135
$\nu_x + d \to n + p + \nu_x$	455	455	455	455
$\bar{\nu}_e + p \to n + e^+$	263	330	326	329
$\nu_e + e^- \to \nu_e + e^-$	4.68	5.68	5.61	5.66
$\bar{\nu}_e + e^- \to \bar{\nu}_e + e^-$	1.54	1.77	1.76	1.77
$\nu_x + e^- \to \nu_x + e^-$	3.87	3.55	3.50	3.53
$\nu_e + ^{16}O \to e^- + ^{16}F$	1.13	14.58	13.78	14.45
$\bar{\nu}_e + ^{16}O \to e^+ + ^{16}N$	4.57	10.62	10.23	10.53
$\nu_x + ^{16}O \to \nu_x + \gamma + X$	13.6	13.6	13.6	13.6

Table 1 The expected number of neutrino events for a 1 kton water cerenkov detector

In Table 1 we report the calculated number of expected events for the main reactions in H_2O and D_2O. Column 2 of Table 1 gives the expected numbers for the model under consideration when the neutrino masses are assumed to be zero. Column 3,4,5 give the corresponding numbers for the two neutrino mixing scenarios that we have considered (see Table 1 for details). All the numbers tabulated have been calculated for 1 kton of detector mass. To get the actual numbers we have to multiply these numbers with the relevant fiducial mass of the detector. The efficiency of both the detectors (SNO and SK) is taken to be 1 [5, 3]. The energy threshold is taken to be 5 MeV for both SK and SNO [3]. For the cross-section of the $(\nu_e - d), (\nu_e - d), (\nu_x - d)$ and $(\bar{\nu}_e - p)$ reactions we refer to [12]. The cross-section of the $(\nu_e(\bar{\nu}_e) - e^-)$ and $(\nu_x - e^-)$ scattering has been taken from [13] while the neutral current $(\nu_x -{}^{16}O)$ scattering cross-section is taken from [3]. For the $^{16}O(\nu_e - e^-)^{16}F$ and $^{16}(\bar{\nu}_e, e^+)^{16}N$ reactions we refer to [14] where we have used the cross-sections for the detector with perfect efficiency. From a comparison of the predicted numbers in Table 1, it is evident that neutrino oscillations play a significant role in supernova neutrino detection. For the neutral current sector the number of events remain unchanged as the interaction is flavour blind. For the Case 1 there is about 98% increase for the ν_e-d events and about 46% increase for the $\bar{\nu}_e$-d events, while the ν_x-d being a neutral current reaction, the number of events remain same even after oscillations are switched on. The noteworthy thing is that even though we have more number of ν_e than ν_e coming from the SN, the signal for $\bar{\nu}_e$-d is more than that for ν_e-d. The reason is that the signal is obtained by folding the fluence with the reaction cross-section. Since for these reactions $\sigma \sim E^{2.3}$ and since the average energy of $\bar{\nu}_e$ is more than that of ν_e, their signal is also more. This also results in a larger enhancement due to oscillations for the ν_e-d events as the difference between the average energies of ν_e and ν_μ is more than that between $\bar{\nu}_e$ and $\bar{\nu}_\mu$. For $\bar{\nu}_e$-p events the increase is about 25% (for Case 1) while for the ν-e scattering reactions the effect is negligible. But the most significant and noteworthy effect of oscillations is seen in the ^{16}O charged current events. The energy threshold for $^{16}O(\nu_e, e^-)^{16}F$ is 15.4 MeV and that for $^{16}O(\bar{\nu}_e, e^+)^{16}N$ is 11.4 MeV, hence these reactions are important only for very high energy neutrinos. The typical average energies of ν_e and $\bar{\nu}_e$ from a type II supernova is about 11 MeV and 16 MeV respectively, so without oscillations these reactions are insignificant. But once oscillations are switched on, mu and tau neutrinos and antineutrinos oscillate (with average energy $\sim$ 25 MeV) into ν_e and $\bar{\nu}_e$ during their flight from the galactic supernova to the detector resulting in higher energy ν_e and $\bar{\nu}_e$ and the number of ^{16}O events are increased appreciably.

In Fig. 1 we plot the ν_e-d signal at SNO as a function of energy without oscillations and with oscillations for the Case 1 and Case 2b. All the features mentioned are clearly seen. The plot for the Case 2b clearly shows oscillations. In Fig. 2 we plot the cumulative fluence of the ν_e coming from the supernova at

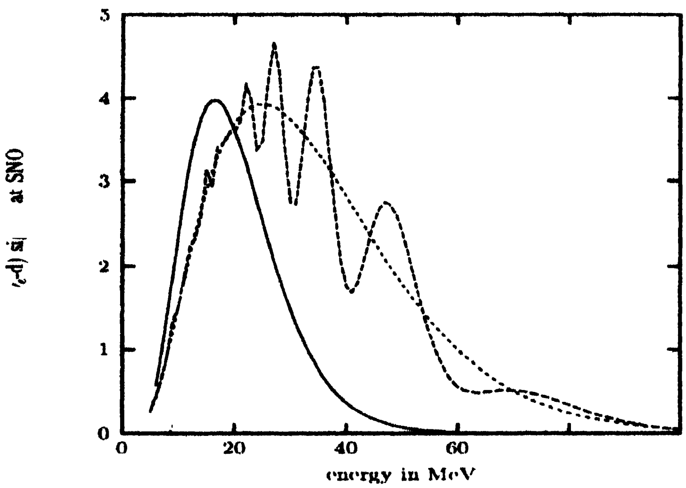

Figure 1. The ($\nu_e - d$ signal versus neutrino energy. The solid line corresponds to the case without oscillations, the long-dashed line with oscillations for Case 2b and the short-dashed line with oscillations for Case 1.

10 kpc without oscillations and with oscillations for Case 1 and Case 2b. From the curve it is evident that the actual number of ν_e falling on the detector in fact goes down due to oscillation. But still we obtain an enhancement in the signal. The answer to this apparent anomaly again lies in the fact that cross-section of these reactions are strongly energy dependent. As a result of oscillations the ν_e flux though depleted in number, gets enriched in high energy neutrinos. It is these higher energy neutrinos which enhance the ν signal at the detector. This also explains the difference in the degree of enhancement for the different processes. For the $(\nu_e - d)$ and $(\nu_e - {}^{16}O)$ events, especially for the latter, the effect is huge while for the $(\nu_e - e^-)$ scattering it is negligible as it's reaction cross-section is only linearly proportional to E. Due to their high energy dependent σ the ${}^{16}O(\nu_e, e^-){}^{16}F$ events turn out to be extremely sensitive to oscillations. A similar argument holds true for the case of the antineutrinos, only here the effect of oscillations is less than in the case for the neutrinos as the difference between the energies of the $\bar{\nu}_e$ and $\bar{\nu}_\mu/\bar{\nu}_\tau$ is comparatively less as discussed earlier.

4. Conclusions

In conclusion, we have shown that with the model of Totani *et al.* even with vacuum oscillations we obtain appreciable enhancement in the expected ν signal in SNO and SK even though the number of neutrinos arriving at the detector from the supernova goes down. In contrast to the case where we have

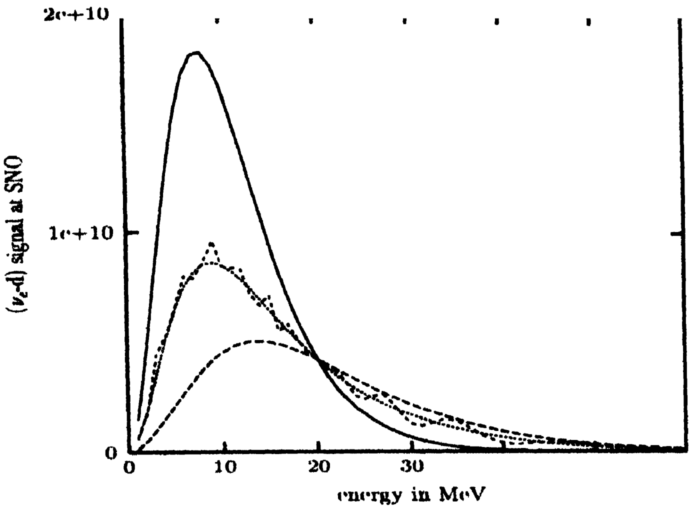

Figure 2. The cumulative neutrino fluence as a function of the neutrino energy. The solid line corresponds to the ν_e fluence without oscillations, while the short dashed line and the dotted line correspond to the ν_e fluence with oscillations for Case 2b and Case 1 respectively. The ν_e fluence without oscillations is shown by the long dashed line.

MSW resonance in the supernova, with vacuum oscillations we get enhancement for both ν_e as well as $\bar{\nu}_e$ events. If we have a galactic supernova event in the near future and if we get a distortion in the neutrino spectrum and an enhancement in the signal, for both ν_e as well as $\bar{\nu}_e$ then that would indicate vacuum neutrino oscillations.

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